COMMISSIONING OF THE RARE-RI RING AT RIKEN RI BEAM FACTORY

Y. Yamaguchi*, Y. Abe, F. Suzaki, M. Wakasugi, and Rare-RI Ring collaborators
RIKEN Nishina Center, Wako, Japan

Abstract

The Rare-RI Ring is an isochronous storage ring to measure masses of short-lived rare nuclei by using relative TOF measurement method. The expected precision of the measured mass is of the order of ppm.

We examined the basic performance of the devices, i.e. injection line, septum magnets, dipole magnets with trim-coils, and fast-kicker system by using α-source in 2014. We demonstrated that trim-coils, which are fixed on the dipole magnets of the ring, can adjust the isochronous condition of the ring. An α-particle was injected into the ring individually by using self-trigger mechanism and was extracted from the ring several turns after the injection.

In June 2015, a commissioning run using a ^{78}Kr beam was performed and basic performances of the Rare-RI Ring were verified. We succeeded in injecting a particle, which was randomly produced from a DC beam using cyclotrons, into the ring individually with the fast-kicker system, and in extracting the particle from the ring less than 1 ms after the injection with same kicker system. We measured time-of-flight (TOF) of the ^{78}Kr particles between the entrance and the exit of the ring to check the isochronism. Through the first-order adjustment with trim-coils, the isochronism on the 10-ppm order was achieved for the momentum spread of ±0.2%. Higher-order adjustment employed in future will lead us to the isochronism on the order of ppm. In addition, we confirmed that a resonant Schottky pick-up successfully acquired the frequency information of one particle in storage mode.

In this paper, the technical aspects of the Rare-RI Ring and the preliminary results of the beam commissioning will be described.

INTRODUCTION

Systematic mass measurements, especially for neutron-rich exotic nuclei very far from the stability, are essential for solving the r-process path. However, nuclei in such regions have very short half-lives and have a very low production rate even with the powerful accelerator complex in RI Beam Factory, therefore, very fast and sensitive apparatus is needed. To this end, we have proposed a unique apparatus, the so called "Rare-RI Ring" about 10 years ago [1], to precisely measure masses of such rare-RIs.

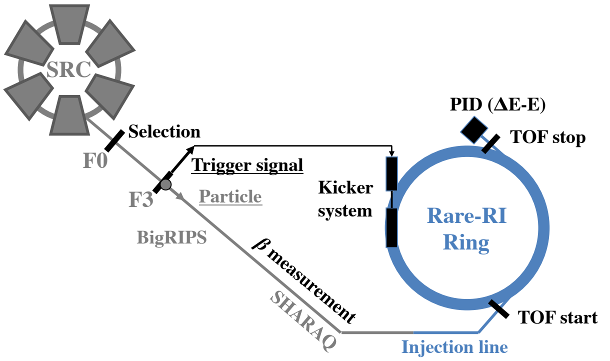

Figure 1: Conceptual design of mass measurement with the Rare-RI Ring.

Figure 1 shows the conceptual design of mass measurement by using the Rare-RI Ring. When a produced secondary particle passes through the timing detector at F3 of the BigRIPS separator [2], a trigger signal is generated. The trigger signal is transmitted to a fast-kicker system via a high speed coaxial tube. Kicker magnets are then immediately excited by thyratrons. In the meanwhile, the particle goes through the BigRIPS separator, the SHARAQ spectrometer [3], and an injection line. The particle that arrives at the entrance of the ring is injected into an equilibrium orbit of the ring using septum and kicker magnets. After the particle revolves in the ring about 700 μs, it is extracted using another septum and the same kicker magnets to measure TOF. In the end, it is identified by ΔE-E detectors. In addition to the short measurement time, this method enables us to measure the mass of even one particle which is suited to measure masses in the r-process region.

PRINCIPLE OF MASS MEASUREMENTS

We adopted the relative mass measurements with references in Isochronous Mass Spectrometry (IMS). In IMS, orbital of the particle is determined by its rigidity. If the rigidity of the particles to be obtained the mass (m_1/q) is the same as that of the reference particle (m_0/q), the flight-pass lengths are identical and the following equations are fulfilled:

$$\frac{m_0}{q}\gamma_0\beta_0 = \frac{m_1}{q}\gamma_1\beta_1, \tag{1}$$

$$\beta_0 T_0 = \beta_1 T_1, \tag{2}$$

where $m_{0,1}/q$ are mass-to-charge ratio, $T_{0,1}$ and $\beta_{0,1}$ are the revolution time and the velocity of the particles with $m_{0,1}/q$ and $\gamma_{0,1} = 1/\sqrt{1-\beta_{0,1}^2}$. By using Eq. (1) and (2), the m_1/q can be expressed as

$$\frac{m_1}{q} = \frac{m_0}{q}\frac{T_1}{T_0}\frac{\gamma_0}{\gamma_1} = \frac{m_0}{q}\frac{T_1}{T_0}\sqrt{\frac{1-\beta_1^2}{1-(\frac{T_1}{T_0}\beta_1)^2}}. \tag{3}$$

---

* yamaguch@ribf.riken.jp

The relative uncertainty of m_1/q is given by

$$\frac{\delta(m_1/q)}{m_1/q} = \frac{\delta(m_0/q)}{m_0/q} + \gamma_0^2 \frac{\delta(T_1/T_0)}{T_1/T_0} + k\frac{\delta\beta_1}{\beta_1}, \quad (4)$$

where

$$k = -\frac{\beta_1^2}{1-\beta_1^2} + (\frac{T_1}{T_0})^2 \frac{\beta_1^2}{1-(T_1/T_0)^2\beta_1^2}. \quad (5)$$

Because the isochronism is basically adjusted to the reference particle, the isochronism for the particle of m_1/q is slightly different. Then the velocity measurement is essential. The coefficient k is on the order of 10^{-2} for $\delta(m/q)$ $\sim \delta T \sim 1\%$. Therefore, mass of the particle within a m/q difference of 1% can be determined with an order of 10^{-6} precision by measuring $T_{0,1}$ with an accuracy of better than 10^{-6} and β_1 with an accuracy of better than 10^{-4} independently, under the condition that the isochronism for a reference particle is optimized with an order of 10^{-6} precision.

THE RARE-RI RING

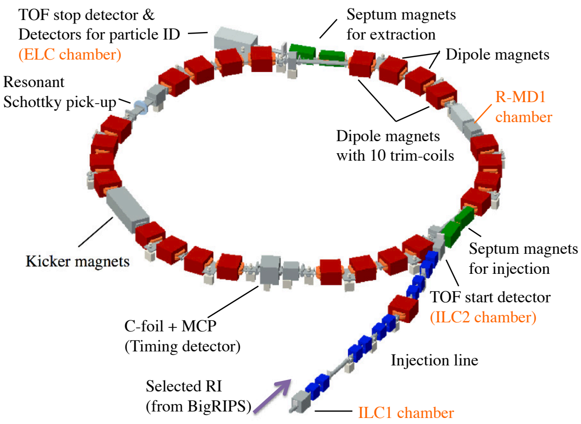

Figure 2: Components of Rare-RI Ring.

Figure 2 shows the components of the Rare-RI Ring. Injection line consists of five quadrupole doublets and one dipole. TOF start detector is located in the ILC2 chamber (see Fig. 2), in addition to two septa for injecting the particles. The ring consists of six magnetic sectors, each consisting of four dipoles. There is no quadrupole for the ring. This dipole is a rectangular magnet with a radially homogeneous magnetic field. The circumference of the ring is about 60.35 m, and the length of a straight section is about 4.02 m. Kicker magnets are located in the position of the phase advance $3\pi/2$ from the injection septa, and the extraction septa are located in the position of the phase advance $3\pi/2$ from the kicker magnets. In order to ensure an isochronism of the ring by making a gradient magnetic field, the two outer dipoles of each magnetic sector were equipped each by ten trim-coils. The ring has beam diagnostic devices in each straight section. Plastic scintillation counters located in all straight sections to check the injection trajectory. Resonant Schottky pick-up [4] and MCP [5] devices are used to measure the frequency of the revolving particle. Figure 3 shows the bird's-eye view photograph of the Rare-RI Ring.

Figure 3: Bird's-eye view photograph of Rare-RI Ring.

Technical Challenges

The individual injection method, which has been proposed in Ref. [6], is a crucial technique for injecting a rare particle into the ring. In order to realize the individual injection, kicker magnets must be excited before the particle arrives at the kicker magnets. For this purpose we constructed a high speed coaxial tube to transmit the trigger signal from F3 of the BigRIPS separator to the kicker system as fast as possible and a fast-response mechanism with thyratron switch to excite the kicker magnets as soon as possible. In addition, fast recharge is necessary to extract a particle from the ring in 700 μs by using same kicker magnets. Therefore, we developed a fast-recharging mechanism, the so called "hybrid charging system", which has main and sub part. Figure 4 shows an example of one set of the Pulse Forming Network (PFN) charging waveform for injection/extraction by using the hybrid charging system. Main part provides 90% of the charging voltage, and the remaining 10% is supplied by sub part of the system. Sub part works to maintain

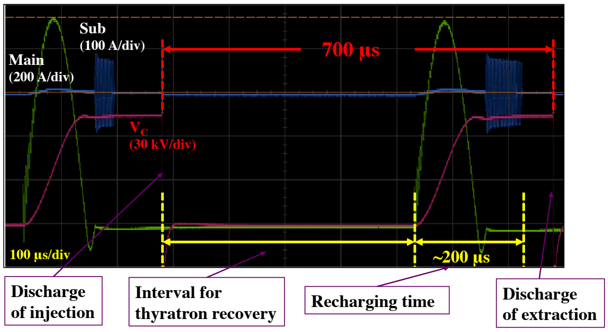

Figure 4: One set of PFN charging waveform for injection/extraction by using the hybrid charging system. Green, blue and red lines indicate the current of main charger, current of sub charger, and PFN charging voltage Vc, respectively.

ISBN 978-3-95450-174-8

a constant charging voltage level within the range of fluctuation of less than ±1%. The time of recharge by this system is achieved in 200 μs. The details of the fast-kicker system can be found in Ref. [7].

Second challenge concerns the isochronous adjustment using trim-coils. We recently performed the isochronous adjustment of the ring with α-particles by using trim-coils. The α-source (^{241}Am) was installed on the central orbit of the ring in the R-MD1 chamber (see Fig. 2). Two detectors were installed just before/after the α-source to measure the TOF of one turn. Then, we checked the condition of the isochronism based on the TOF width. Figure 5 shows the results of the TOF width as a function of the first-order trim field ($(dB/dr)/B_0$). The minimum value of the TOF width is obtained with $(dB/dr)/B_0 = 0.205$ m^{-1}. This is consistent with the results calculated by using the α-source energies, which confirmes that the trim-coils play the role of adjusting the isochronism. The details of the study by using the α-source can be found in Ref. [8].

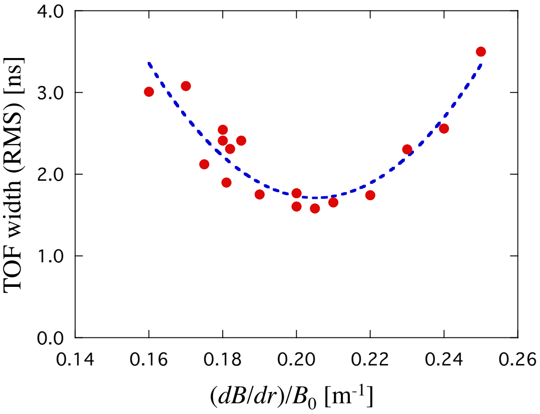

Figure 5: TOF width of one turn of α-particles as a function of the first-order trim field $(dB/dr)/B_0$.

BEAM COMMISSIONING

In June 2015, we performed a beam commissioning using ^{78}Kr with 168 MeV/u, the energy of which matches to the individual injection. Specifications of the ring for this commissioning are given in Table 1.

Table 1: Specifications of the Ring for this Commissioning

Transition γ_{tr}	1.18
Betatron tune	$\nu_x = 1.18$, $\nu_y = 0.93$
Beta function	$\beta_x = 8.4$ m, $\beta_y = 11.9$ m
Dispersion	7.0 m
Kick angle	11 mrad

First, we transported the beam to the ring with a dispersion matching at the center of kicker magnets in accordance with the optical calculations. After that, we injected ^{78}Kr particles individually on the equilibrium orbit of the ring using the fast-kicker system. We confirmed the periodic signals of the circulating particles with the MCP, which is located on the closed orbit of the ring. Figure 6 shows the TDC (Aquiris TC890) spectrum for circulating particles. The particle cannot be stored for long time and it's lost after 25 μs due to the penetration efficiency at the MCP material. After removing the MCP from the closed orbit, we succeeded in extracting the circulating particles from the ring after 700 μs.

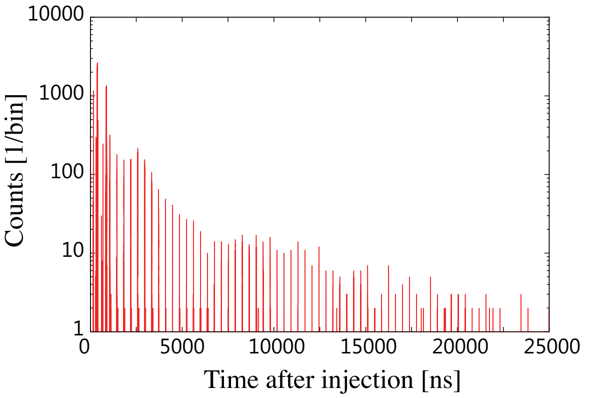

Figure 6: TDC (Aquiris TC890) spectrum for circulating particles.

Isochronism

Figure 7 shows the TOF of ^{78}Kr particles as a function of the momentum spread with different values of the $(dB/dr)/B_0$. We understand from this figure that the ex-

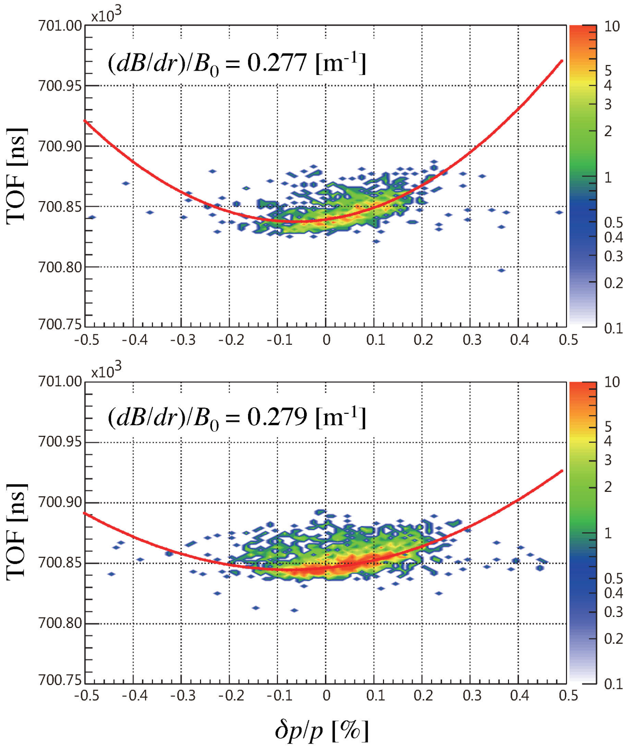

Figure 7: TOF spectra as a function of the momentum spread with different value of $(dB/dr)/B_0$. Red lines shows the quadratic fitting curve of TOF spectra.

tractable momentum spread is about ±0.2 %. The TOF width of $(dB/dr)/B_0 = 0.279\ \mathrm{m}^{-1}$ is about 25 ns in FWHM as a result of fitting in the projection on the vertical axis. Therefore, the degree of isochronism is about 3.5×10^{-5} for the momentum spread of ±0.2 %.

The value of $(dB/dr)/B_0 = 0.279\ \mathrm{m}^{-1}$ is an optimum value by using a numerical analysis. However, the experimental optimum value of it may be a little bigger since the quadratic curve is still not symmetry. We haven't enough time to tune the first-order trim field any further, but we were able to achieve a 10-ppm isochronism by adjusting the first-order trim field.

Resonant Schottky Pick-up

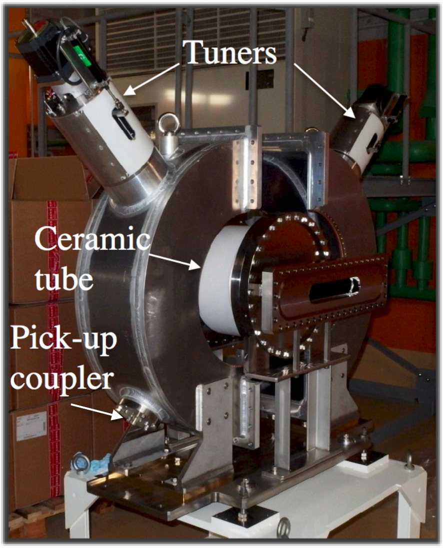

Figure 8: Photograph of resonant Schottky pick-up.

Resonant Schottky pick-up consists of a pillbox-type resonant cavity and ceramic gap, as shown in Fig. 8. Outer diameter, length, and inner diameter of the cavity are 750 mm, 200 mm, and 320 mm, respectively. When a particle pass through the resonant Schottky pick-up, an electromagnetic field is induced in the cavity. The change of magnetic flux in the induced electromagnetic field is detected by a pick-up loop. The coupling factor of the pick-up loop was optimized to be one. By adjusting the position of two tuners, the resonance frequency can change in the range of 173±1.5 MHz. In addition, the shunt impedance Rsh is 161 kΩ and the unloaded quality factor Q_0 is 1880, respectively.

In this beam commissioning, we verified that a resonant Schottky pick-up successfully acquired the frequency information of one ^{78}Kr particle in a storage mode. The frequency resolution is about 1.3×10^{-6} in FWHM, which is sufficient resolution as a monitor for the isochronous adjustment.

A particle was stored in the ring about 4 seconds while changing its frequency, as shown in Fig. 9. The change in frequency is due to the poor degree of vacuum in the ring, and the shape of curve is influenced by the isochronism for each momentum. Black line in Fig. 10 shows the Schottky data obtained by converting Fig. 9 to understand this phenomena. The revolution time was calculated from the resonance frequency using the number of harmonics. The degree of vacuum was about 4×10^{-5} at the worst point in the ring, and we assumed H_2O as a residual gas to calculate the momentum. The tendency of the black line is consistent with that of the quadratic fitting curve of TOF spectrum.

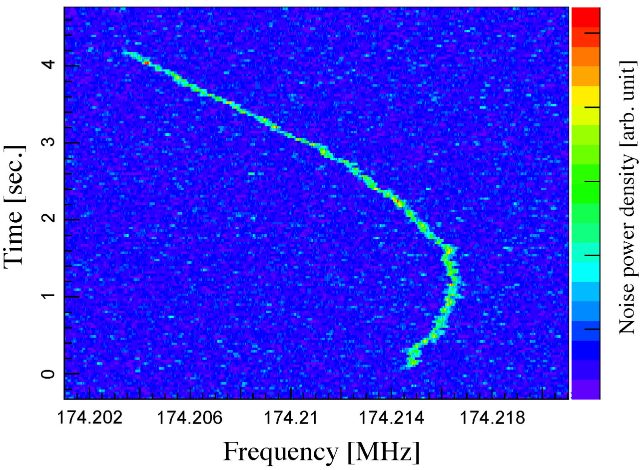

Figure 9: Frequency information of one ^{78}Kr particle from resonant Schottky pick-up.

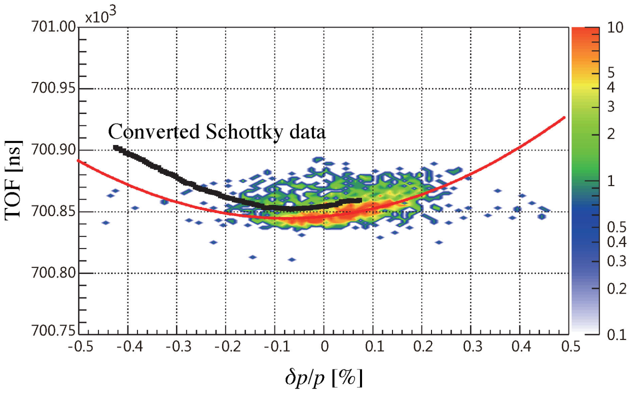

Figure 10: Black line shows converted Schottky data coupled with the result of TOF spectrum of $(dB/dr)/B_0 = 0.279\ \mathrm{m}^{-1}$.

SUMMARY AND PROSPECTS

^{78}Kr beam commissioning run was conducted successfully and the off-line analysis is in progress. First-oder trim field can adjust the isochronism in an order of 10-ppm. To achieve more higher isochronism, we will perform second-order adjustment with trim-coils. Then, the resonant Schottky pick-up can be used for checking the isochronism.

We are planning the next commissioning using the secondary particles to verify the principle of mass measurements in December 2015. The mass measurement experiments will start from 2016. On the other hand, the lifetime measurement of rare-RIs using the resonant Schottky pick-up is also planned. We need to improve the degree of vacuum in the ring by baking to do it. In the future, we will also be carried out the nuclear reaction experiments, such as proton elastic scattering and so on, using an internal target with a RF cavity.

ACKNOWLEDGMENT

Beam commissioning was performed at RI Beam Factory operated by RIKEN Nishina Center and CNS, University of Tokyo. This work was partially supported by JSPS KAKENHI no. 26287036.

REFERENCES

[1] Y. Yamaguchi, et al., “Rare-RI ring project at RIKEN RI beam factory”, Nucl. Instrum. and Methods, B266, 4575 (2008).

[2] T. Kubo, “In-flight RI beam separator BigRIPS at RIKEN and elsewhere in Japan”, Nucl. Instrum. and Methods, B204, 97 (2003).

[3] T. Uesaka, et al., “The SHARAQ spectrometer”, Prog. Theor. Exp. Phys, 03C007 (2012).

[4] F. Suzaki, et al., “Performance of a resonant Schottky pick- up for Rare-RI Ring project”, JPS Conf. Proc. 6, 030119 (2015).

[5] Y. Abe, et al.,“Developments of time-of-flight detectors for Rare-RI Ring”, JPS Conf. Proc. 1, 013059 (2014).

[6] I. Meshkov, et al., “Individual rare radioactive ion injection, cooling and storage in a ring”, Nucl. Instrum. and Methods, A523, 262 (2004).

[7] Y. Yamaguchi, et al., “Fast-kicker system for rare-RI ring”, Proc. of STORI’14, Sankt Goar, Germany (2014).

[8] Y. Abe, et al., “Isochronous field study of the Rare-RI Ring”, Proc. of STORI’14, Sankt Goar, Germany (2014).